

Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth

Nicholaus D. VanWoert, D. Bradley Rowe,* Jeffrey A. Andresen, Clayton L. Rugh, R. Thomas Fernandez, and Lan Xiao

ABSTRACT

Urban areas generate considerably more stormwater runoff than natural areas of the same size due to a greater percentage of impervious surfaces that impede water infiltration. Roof surfaces account for a large portion of this impervious cover. Establishing vegetation on rooftops, known as green roofs, is one method of recovering lost green space that can aid in mitigating stormwater runoff. Two studies were performed using several roof platforms to quantify the effects of various treatments on stormwater retention. The first study used three different roof surface treatments to quantify differences in stormwater retention of a standard commercial roof with gravel ballast, an extensive green roof system without vegetation, and a typical extensive green roof with vegetation. Overall, mean percent rainfall retention ranged from 48.7% (gravel) to 82.8% (vegetated). The second study tested the influence of roof slope (2 and 6.5%) and green roof media depth (2.5, 4.0, and 6.0 cm) on stormwater retention. For all combined rain events, platforms at 2% slope with a 4-cm media depth had the greatest mean retention, 87%, although the difference from the other treatments was minimal. The combination of reduced slope and deeper media clearly reduced the total quantity of runoff. For both studies, vegetated green roof systems not only reduced the amount of stormwater runoff, they also extended its duration over a period of time beyond the actual rain event.

URBAN STORMWATER RUNOFF has come to the forefront as an environmental concern. The USEPA has indicated that a typical city block generates more than five times as much runoff than a woodlot of the same size (USEPA, 2003). Urban stormwater runoff carries with it numerous environmental contaminants including pesticides, heavy metals, and nutrients, which may eventually flow into lakes and streams (Bucheli et al., 1998; Mason et al., 1999). According to the USEPA (2003), "The most recent National Water Quality Inventory reports that runoff from urbanized areas is the leading source of water quality impairments to surveyed estuaries and the third-largest source of impairments to surveyed lakes."

Establishing vegetation on rooftops, commonly referred to as green roofs, is an emerging strategy for mitigating stormwater runoff (Monterusso et al., 2004; Moran et al., 2003; Rowe et al., 2003; Schade, 2000). In addition, green roofs offer numerous other benefits beyond stormwater mitigation. They provide insulation for buildings,

thus saving on energy consumption (Niachou et al., 2001; Wong et al., 2003); increase the life span of a typical roof by protecting the roof components from damaging ultraviolet rays, extreme temperatures, and rapid temperature fluctuations (Giesel, 2001); filter harmful air pollutants (Liesecke and Borgwardt, 1997); provide a more aesthetically pleasing environment to live and work; provide habitat for a range of organisms from microbes to birds (Brenneisen, 2003; Gedge, 2003); and have the potential to reduce the Urban Heat Island Effect (Dimoudi and Nikolopoulou, 2003; Rosenfeld et al., 1998; Wong et al., 2003).

However, many consider stormwater runoff mitigation to be the primary benefit of green roofs due to the prevalence of impervious surfaces in urban and commercial areas and a failing stormwater management infrastructure (Liptan, 2003). Rapid runoff from roofs and other impervious surfaces can exacerbate flooding, increase erosion, and result in combined sewer overflows that could potentially discharge raw sewage directly into our waterways. Green roofs help mitigate the impact of high-density commercial and residential development by restoring displaced vegetation. Studies have shown that green roofs can absorb water and release it slowly over a period of time as opposed to a conventional roof where stormwater is immediately discharged (Liesecke, 1999; Moran et al., 2003; Schade, 2000). Research has indicated that an extensive green roof, depending on substrate depth, can retain 60 to 100% of incoming rainfall (Liesecke, 1998; Monterusso et al., 2004; Schade, 2000).

This reduction in quantity of runoff from a green roof leads to improved stormwater runoff and surface water quality. Results from a Vancouver, BC, modeling study suggest that if all of Vancouver's existing buildings were retrofitted with green roofs over the next 50 yr, the health of the area watershed could be restored to natural hydrologic conditions in terms of flood risk, aquatic habitat, and water quality (Graham and Kim, 2003). This would occur because green roofs have the ability to filter numerous contaminants from rainwater that has flowed across the roof surface (Dramstad et al., 1996). Although minimal, Bucheli et al. (1998) detected concentrations of three common classes of pesticides in non-green roof runoff due to atmospheric deposits. Other studies showed roof runoff contained higher amounts of numerous heavy metals and nutrients when compared with rainfall, probably due to the runoff picking up particulate pollutants when flowing across the roof (Mason et al., 1999). For green roofs, these pollutants can be taken up and degraded by the plants or bound in the growing substrate of green roofs (Johnston and Newton, 1996). Zobrist et al. (2000) concluded that without corrective measures, roof runoff pollutants will lower the water quality of surrounding water bodies.

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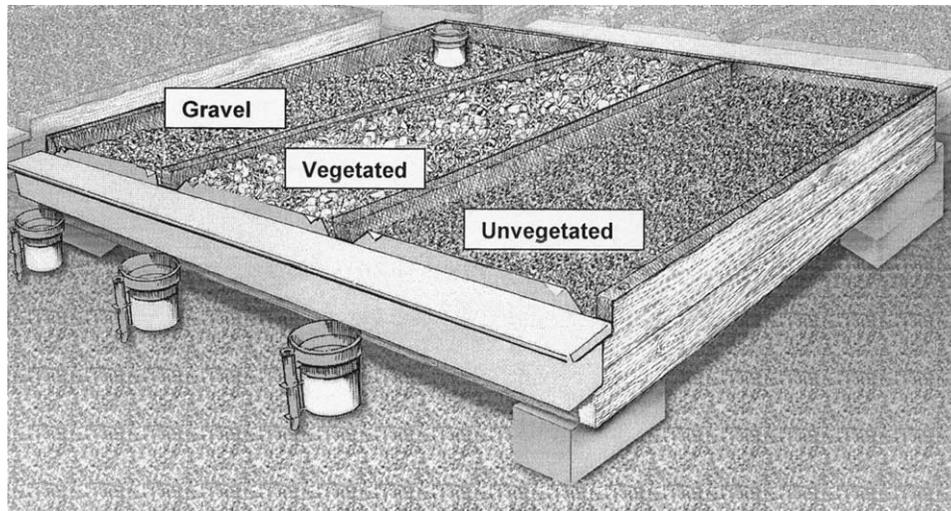


Fig. 1. Graphic representation of the model-scale roof platforms used to evaluate stormwater retention in the roof surface comparison study.

An estimated 14% of all flat roofs are green in Germany, a nation widely considered the leader in green roof research, technology, and usage (Herman, 2003). In North America, the concept of green roofs is in its infancy. If green roof installations are to become commonplace in the United States, quantifiable data that document the ability of green roofs to retain stormwater under the climatic conditions of the region must be available. Data of this nature exist for particular drainage systems in other areas of the continent and Europe, but most is not transferable to these specific climatic conditions. Also, much of the current information is anecdotal in nature, the information is proprietary, or the experiments were not performed in a replicated study. Therefore, our objective was to quantify the differences in water retention among an extensive green roof, an extensive green roof without vegetation, and a standard gravel ballast roof in a replicated study. In addition, studies were performed with the objective to quantify the differences in water retention among various substrate depths and roof slopes in a replicated study. This information can then be used to make decisions concerning green roof usage to mitigate stormwater runoff and can potentially be used to develop models to predict stormwater runoff during the design of green roof systems.

MATERIALS AND METHODS

Study 1

Platforms

Three simulated roof platforms with overall dimensions of 2.44×2.44 m were constructed by ChristenDetroit (Detroit, MI) at the Michigan State University Horticulture Teaching and Research Center (East Lansing, MI) (Fig. 1). Each platform simulated a commercial roof, including an insulation layer, protective layers, and waterproofing membrane. However, since there was not an environmentally controlled room under the platform, heat flux through the roof can be discounted. Platforms were divided into three equal sections measuring 0.67×2.44 m using wood dividers that were also covered with the waterproofing membrane. Lining the platform deck was 3.8 cm of ENRGY 2 insulation board (Johns Man-

ville, Denver, CO), composed of a closed cell polyisocyanurate foam core and fiberglass reinforced facers. Above the ENRGY 2 layer was a 1.9-cm-thick insulation layer of Fesco board consisting of expanded perlite, blended with selected binders and fibers (Johns Manville). The top layer was a combination of Paradiene 20 (Siplast, Irving, TX), a flexible membrane with an elastomeric asphalt base, and Teranap (Siplast), a polyester mat coated with styrene butadiene styrene (SBS)-modified bitumen, with a root-resistant polyester film covering the top side.

Aluminum sheet metal troughs were attached on the low end of the platforms to direct stormwater runoff through the measuring devices used to quantify runoff. Each trough was divided into three separate sections corresponding to the three divided sections. The wood-framed platforms included sides that extended 20.3 cm above the platform deck, also covered with the waterproofing membrane. Platforms were set at a 2% slope with the top edge of the high end 0.9 m above ground level and oriented with the low end of the slope facing south to maximize sun exposure.

Drainage System and Vegetation Carrier

Two of the three self-contained sections on each platform used the Xero Flor XF108 drainage layer (Wolfgang Behrens Systementwicklung GmbH, Groß Ippener, Germany) installed over the Teranap Waterproofing System (Fig. 2). The drainage

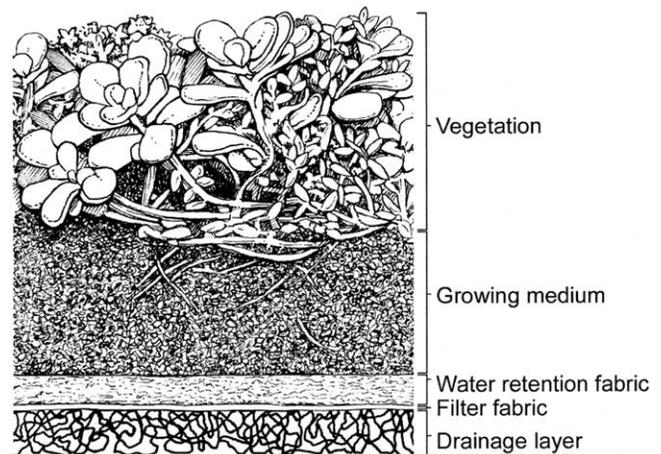


Fig. 2. Cross-section of a representative extensive green roof system including typically used layers.

Table 1. Potential water retention capacity of the green roof system components used in Studies 1 and 2.

Component	Rainfall retention capacity
	mm
Water retention fabric (1.5 cm)	2
Media (2.5 cm)	5
Media (4.0 cm)	8
Media (6.0 cm)	12

layer consisted of a geotextile fabric with nylon coils attached on the underside. The total thickness of this layer was approximately 1.5 cm. For additional water holding capacity, a 0.75-cm-thick water retention fabric (Xero Flor XF158) capable of retaining up to 1200 g m⁻² of water was placed over the drainage layer. The water retention fabric was composed of a recycled synthetic fiber mixture consisting of polyester, polyamide, polypropylene, and acrylic fibers. Above this additional retention fabric was the vegetation carrier (Xero Flor XF301), which included a recycled synthetic fiber fabric similar to XF158 used for water retention sewn to an inverted layer of XF108 that held media and vegetation. This water retention layer could hold up to 800 g m⁻² of water and was approximately 0.75 cm thick. There was then 2.5 cm of growing media placed on the vegetation carrier. The water retention fabric in combination with the 2.5 cm of growing media have the potential to hold up to 7 mm of rainfall (Table 1). Total thickness of the drainage layer, vegetation carrier, and growing media was approximately 5.5 cm. The system as a whole permits water exceeding the holding capacity of the retention fabric and planting media to drain through the nylon coils and exit the roof.

Plant Establishment

One hundred percent coverage (no visible growing media) was achieved on the vegetated section before the initiation of data collection. Plant species used in this study included golden carpet (*Sedum acre* L.), stonecrop (*S. album* L., *S. kamtschaticum ellacombianum* Fisch., and *S. pulchellum* Michx.), stone orpine (*S. reflexum* L.), and two-row stonecrop (*S. spurium* Bieb. 'Coccineum' and 'Summer Glory'). The plant mix was applied as seed on 14 May 2002 at a rate of 1.3 g m⁻² for each species. All seeds were evenly mixed in dry sand to ensure even distribution when the mixture was sown by hand on the platforms. Seeds were obtained from Jelitto Staudensamen GmbH (Schwarmstedt, Germany).

Growing media consisted of 40% heat-expanded slate (gradation 3–5 mm) (PermaTill; Carolina Stalite Company, Salisbury, NC), 40% USGA (United States Golf Association)-grade sand (Osburn Industries, Taylor, MI), 10% Michigan Peat (Osburn Industries), 5% dolomite (Osburn Industries), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, MI), and 1.67% composted poultry litter (Herbruck's, Saranac, MI) by volume. Media bulk density, capillary pore space, noncapillary pore space, infiltration rate, and water holding capacity at 0.01 MPa were 130 kg m⁻³, 19.9%, 21.4%, 51.6 cm h⁻¹, and 17.1%, respectively (A & L Laboratories, Fort Wayne, IN). Saturated weight was equal to 150 kg m⁻³. At time of planting, electrical conductivity (EC) and pH of the media were 0.33 S m⁻¹ and 7.9, respectively. Each green roof system platform section was filled with planting media to a depth of 2.5 cm. All sections of the platforms, except gravel, had 100 g m⁻² of Nutricote Type 100, 20N-7P₂O₅-10K₂O controlled release fertilizer (Agrivert, Webster, TX) hand-applied at the time of planting and on 19 May 2003.

Platforms were covered with a plastic shade cloth (Wolfgang Behrens Systementwicklung GmbH) for the first 52 d after the seed was sown to enhance germination and plant establish-

ment. Seedlings were acclimated from Days 52 through 57 by periodically removing the shade cloth depending on the intensity of the sun, after which it was removed permanently.

Upon seed distribution, an automated overhead irrigation system (Rainbird, Azusa, CA) was programmed to run six 10-min cycles daily (0900, 1100, 1300, 1500, 1700, and 1900 h) through 15 July 2002. From 16 July until 31 July 2002, the irrigation was reduced to four 10-min cycles daily (0900, 1300, 1700, and 1900 h). Irrigation was terminated on 31 July 2002 once the plants had become established and had achieved 100% coverage.

Roof Treatments

Three roof types were tested: an extensive green roof with vegetation, an extensive green roof without vegetation (media-only), and a conventional commercial roof with a 2-cm depth gravel ballast. A gravel ballast is commonly used on flat commercial roofs to hold the waterproofing membrane in place. The vegetated and media-only sections each contained a green roof drainage system and vegetation carrier as described previously. Roof treatments were arranged in a randomized complete block design (RCBD) with three replications; each platform represented one block and the vegetation, media-only, or gravel ballast treatment was randomly assigned within sections of each platform (Fig. 1).

Data Collection and Analysis

Model TE525WS tipping bucket rain gauges (Campbell Scientific, Logan, UT) were mounted under the drain of each platform section to quantify stormwater runoff. An additional tipping bucket was mounted above each gravel section to record precipitation, catching and releasing quantified water onto the top end of the gravel surface. A Model CM6 automated weather station (Campbell Scientific) was installed on the research site to record meteorological parameters. The weather station included an ambient air temperature and relative humidity probe covered by a six-plate gill radiation shield. The weather station also included instruments to measure wind speed and direction as well as photosynthetically active radiation.

Data from the tipping bucket rain gauges and tripod weather station were collected at 5-min intervals 24 h a day from 28 Aug. 2002 through 31 Oct. 2003 using a Campbell Scientific CR10X datalogger equipped with switch closure modules and a storage module. Accuracy of the rain gauges was ±1%, +0 and -2.5%, and +0 and -3.5% for rainfalls of <25.4 mm h⁻¹, 25.4 to 50.8 mm h⁻¹, and 50.8 to 76.2 mm h⁻¹, respectively. During the largest rain event over the course of the study, 96.8% of the rain that fell on the conventional gravel roof platforms was recorded exiting the roofs by the tipping bucket rain gauges. The other 3.2% either evaporated or can be attributed to error. Although the raw data indicate otherwise, runoff values from the conventional roof platforms with the gravel ballasts may be underestimated during some of the heavier rain events.

Retention data were analyzed from all rain events that occurred during temperatures above 0°C as a percentage of total rainfall for each rain event. Frozen precipitation was not physically removed from the platforms. Melting precipitation was allowed into the data set if it fully occurred in temperatures above 0°C. Independent rain events were defined as precipitation events separated by six or more hours. In the event runoff was still occurring six hours after the first event, the two events were combined. Rain events were arbitrarily categorized as light (<2 mm), medium (2–6 mm), or heavy (>6 mm). The extent of each category was chosen to get rain event sample sizes that were similar across all three categories.

Data were analyzed as mean percent retention per rain

event using an ANOVA model with platform as a random effect and roof treatment and rainfall category as fixed effects. Although original means are presented, all runoff values were transformed before analysis using a power transformation (0.4) to stabilize the variance and normalize the data. Significant differences between treatments were determined using multiple comparisons with Tukey–Kramer adjustments (PROC MIXED, SAS Version 8.02; SAS Institute, 2001). Total retention values for the study are presented, but were not subjected to statistical analysis due to the limited number of data points.

Study 2

Twelve additional roof platforms were used to examine roof slope and media depth. These platforms were constructed as previously described, except that each 2.44- × 2.44-m platform was considered an experimental unit as the platforms were not divided into three equal sections. All platforms had vegetated extensive green roof systems installed as described previously and were subjected to the same environmental conditions, and runoff data were collected with identical instrumentation and protocols.

Treatments were arranged in a completely randomized design (CRD) with three replications. Six platforms were set at a 2% slope and six were set at a 6.5% slope. A total of three growing media depths were examined, with two depths tested at each slope. For the 2% slope, media depths of 2.5 and 4.0 cm were tested while depths of 4.0 and 6.0 cm were tested on the 6.5% slope platforms. Potential water retention capacity of the water retention fabric and growing media is shown in Table 1.

Data were analyzed as mean percent retention per rain event using an ANOVA model with roof slope, media depth, and rainfall category as fixed effects. Although original means are presented, all retention values were transformed before analysis using a power transformation (0.113) to stabilize the variance and normalize the data set. Significant differences between treatments were determined using multiple comparisons with Tukey–Kramer adjustments (PROC MIXED, SAS Version 8.02; SAS Institute, 2001). Total retention values for the study are presented, but were not subjected to statistical analysis due to the limited number of data points.

RESULTS

Measurable precipitation (>0 mm) was recorded on 162 of the 430 d of the study (38%) (Fig. 3). Daily precipitation amounts ranged from 0.08 to 53.59 mm. Of the 83 rain events measured during temperatures above 0°C, there were 26 light (<2 mm), 30 medium (2–6 mm), and 27 heavy (>6 mm) rain events. Generally, low-volume rain events were more frequent than larger rain events. Daily maximum and minimum ambient air temperatures ranged from -9.9 to 34.2°C and -24.6 to 20.8°C, respectively.

Study 1

Representative hydrographs (Fig. 4) and cumulative hydrographs (Fig. 5) from a selected rain event within each rainfall category show the effects that the roof treatments had on quantity, delay of the start, and time duration of runoff. During a representative light rain event, the start of runoff from the vegetated treatments did not begin until 55 min after the initial rainfall was measured. This delay was 15 min after the time when runoff was de-

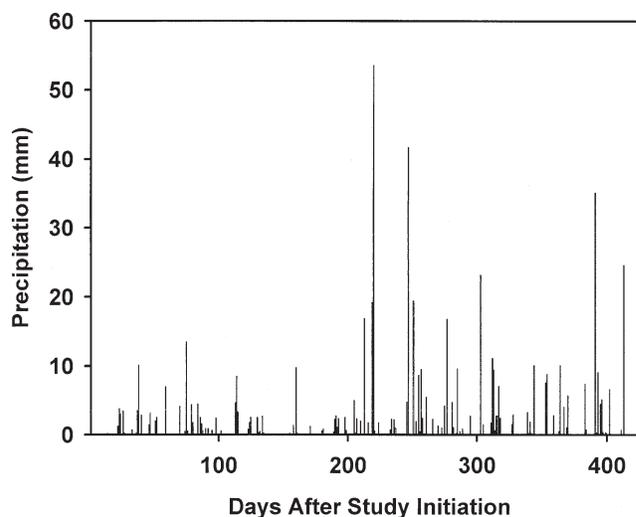


Fig. 3. Daily precipitation (mm) during the experimental study (28 Aug. 2002 through 31 Oct. 2003). Values are averages of measurements taken using three tipping bucket rain gauges mounted at the research site.

tected from the gravel ballast treatment. The start of runoff from the gravel treatments was delayed 10 min past the initial rainfall during the representative medium rain event, and 15 min for both the media-only and vegetated treatments. Following a delay of 15 min after the initial rainfall, runoff from all treatments was de-

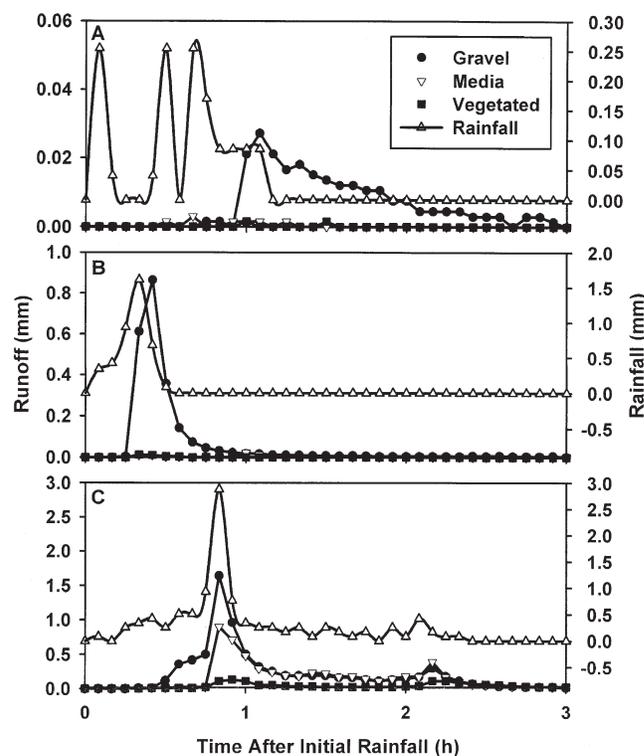


Fig. 4. Runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events recorded at 5-min intervals. Lines represent either rainfall (mm) or runoff (mm) from conventional roofs with a gravel ballast (gravel), nonvegetated green roofs with media only (media), or vegetated green roof treatments (vegetated). Values are averages of measurements taken using three tipping bucket rain gauges.

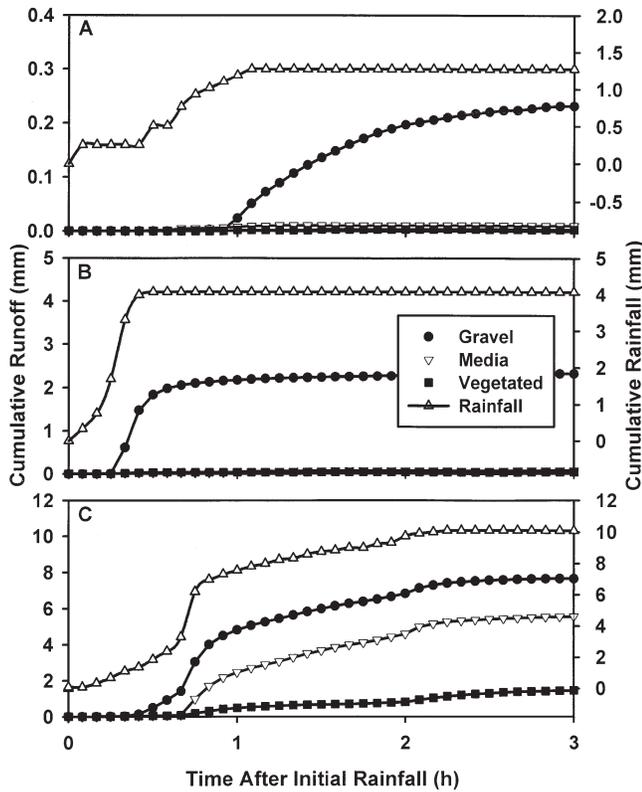


Fig. 5. Cumulative runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events recorded at 5-min intervals. Lines represent either rainfall (mm) or runoff (mm) from conventional roofs with a gravel ballast (gravel), nonvegetated green roofs with media only (media), or vegetated green roof treatments (vegetated). Values are averages of measurements taken using three tipping bucket rain gauges.

tected within 5 min of each other during the representative heavy rain event. Runoff was not only delayed during the heavy rain event with the media-only and vegetated treatments, it was spread out over time; the last measured runoff was recorded nearly 3 h after the rain event ended, which was 30 min past the last runoff from the gravel ballast treatment.

Over the 14-mo period, the vegetated roof treatment retained 337 mm of the 556 mm of cumulative rainfall from the 83 measured rain events (60.6%) (Table 2). The media-only treatment retained 281 mm (50.4%) and, as expected, the gravel ballast roof retained the least rainfall, 151 mm (27.2%). When total rainfall from all light rain events was combined (25 mm), the media-

Table 2. Percentage of total rainfall retention over the 14-mo period (28 Aug. 2002 to 31 Oct. 2003) from three roof platform treatments replicated three times.

Treatment†	Light‡	Medium	Heavy	Overall
	%			
Gravel	79.9	33.9	22.2	27.2
Media	99.3	82.3	38.9	50.4
Vegetated	96.2	82.9	52.4	60.6

† Values denote retention from conventional roofs with a gravel ballast (gravel), nonvegetated green roofs with media only (media), and vegetated green roofs (vegetated).

‡ Rain event categories are light (<2 mm) (n = 26), medium (2–6 mm) (n = 30), heavy (>6 mm) (n = 27), and overall (n = 83).

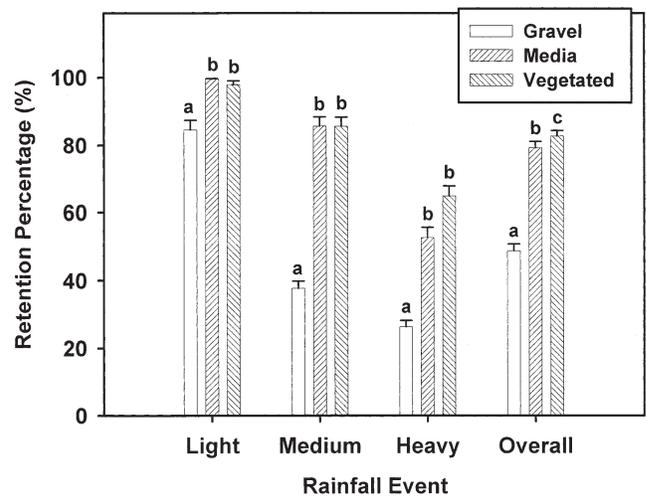


Fig. 6. Retention percentage (%) averaged for all measured rain events in respective categories (light, n = 26; medium, n = 30; heavy, n = 27; overall, n = 83) for each roof treatment. Letters above bars represent mean separation among treatments within each rainfall category by Tukey's Studentized Range (HSD) test, $P \leq 0.05$, n = 3. Error bars represent standard error symmetrical around the mean, but only the positive side is shown on the graph.

only and vegetated treatments each retained greater than 96% of the rainfall. For combined medium rain events (113 mm), the gravel ballast treatment retained the least (33.9%) and the vegetated treatment retained the most (82.9%) rainfall. The same trend occurred for combined heavy rain events (418 mm) with gravel ballast retaining 22.2% and vegetated retaining 52.4% of the rainfall (Table 2).

When rainfall was separated into distinct rain events and retention percentages from each rain event were averaged together, retention percentages were lowest for the gravel ballast, followed by the media-only, and vegetated roof treatments; all means were different ($P \leq 0.05$) (Fig. 6). However, when the rain events were categorized into light, medium, and heavy, the media-only and the vegetated treatments were not different in any of the rainfall categories, although both were different from the gravel ballast treatment. The lowest retention percentage for all treatments occurred during heavy rain events where 26.3, 52.6, and 65.0% was retained for the gravel ballast, media-only, and vegetated treatments, respectively. During medium rain events, the media-only and vegetated treatments each retained an average of 85.7% of the rainfall per rain event. The gravel ballast treatment retained an average of 37.7% of the rainfall for these events. The gravel ballast treatment retained an average of 84.6% of the rainfall for the light rain events, followed by the vegetated treatment (97.9%) and media-only (99.6%).

All treatments retained 100% of the rainfall from a rain event on several occasions. This occurred seven, fifteen, and twenty times on the gravel ballast, media-only, and vegetated treatments, respectively. The heaviest rainfall for which 100% retention was achieved for the vegetated treatment was 5.56 mm. This was likely possible because substrate moisture content was relatively low before the rain event. There was zero precipitation dur-

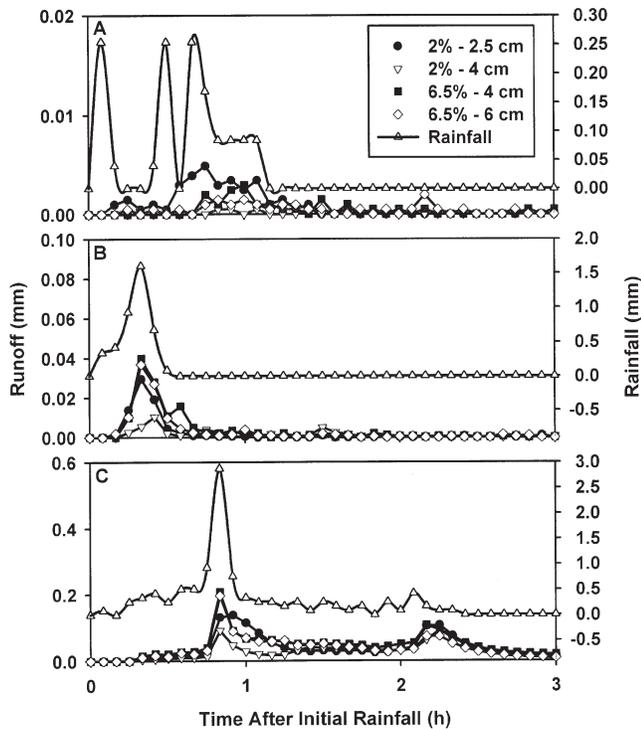


Fig. 7. Runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events recorded at 5-min intervals. Lines represent either rainfall (mm) or runoff (mm) from vegetated green roof platforms set at a 2% roof slope with 2.5 cm of media (2%–2.5 cm), 2% roof slope with 4 cm of media (2%–4 cm), 6.5% roof slope with 4 cm of media (6.5%–4 cm), or 6.5% roof slope with 6 cm of media (6.5%–6 cm). Values are averages of three replications measured using tipping bucket rain gauges mounted at the research site.

ing the previous five days and the average high ambient temperature was 29.8°C. For the gravel ballast treatment, the heaviest event with complete retention was 0.76 mm. The least retention (12%) from the vegetated treatment occurred during a rain event of 73 mm that spanned three days. Individual rain event retention percentages under 15% occurred numerous times for the gravel ballast treatment during rain events ranging from 0.68 to 73 mm.

Study 2

Representative hydrographs (Fig. 7) and cumulative hydrographs (Fig. 8) from a selected rain event within each rainfall category show the effect that slope and media depth had on quantity of runoff, as well as their ability to delay runoff. Initial runoff from all four treatments occurred within 10 min of each other for both the medium and heavy representative rain events. During the representative light rain event, runoff from both treatments with 4 cm of media was delayed 30 to 40 min compared with the 2%–2.5 cm and 6.5%–6 cm treatments. Runoff was not only delayed during the representative heavy rain event, it was spread out over time; the last measured runoff from the platforms occurred 14 h after the rain event ended.

Over the 14-mo period, the roof platforms retained more than 68% of the 556 mm of the measured rainfall.

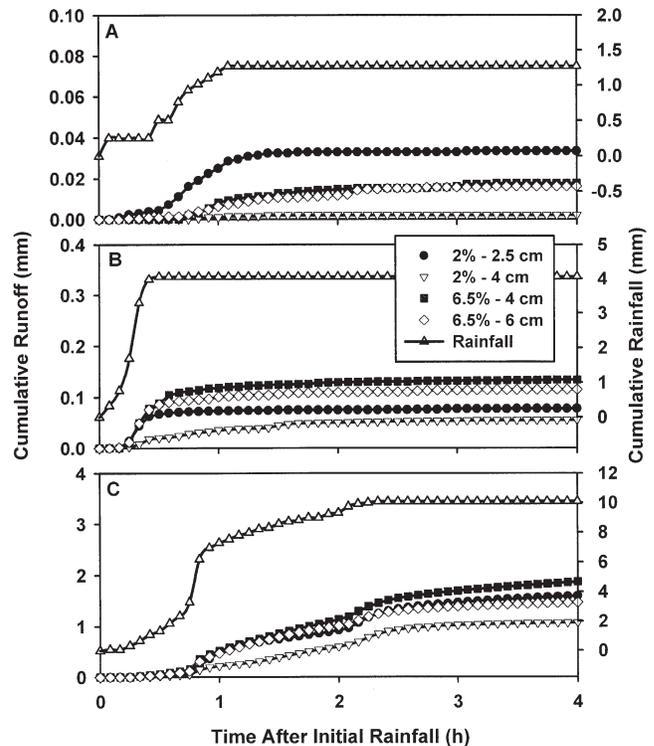


Fig. 8. Cumulative runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events recorded at 5-min intervals. Lines represent either rainfall (mm) or runoff (mm) from vegetated green roof platforms set at a 2% roof slope with 2.5 cm of media (2%–2.5 cm), 2% roof slope with 4 cm of media (2%–4 cm), 6.5% roof slope with 4 cm of media (6.5%–4 cm), or 6.5% roof slope with 6 cm of media (6.5%–6 cm). Values are averages of three replications measured using tipping bucket rain gauges mounted at the research site.

Individually, the 6.5% sloped platforms containing 4 cm of media retained the least amount of rainfall (65.9%) (Table 3). Retention ranged from 97.1% (2%–2.5 cm) during light rain events to 59.5% (6.5%–4 cm) for heavy rain events (Table 3).

When total rainfall was separated into distinct rain events and retention percentages were averaged together, overall retention percentages ranged from 83.8% (6.5%–4 cm) to more than 87% (2%–4 cm) when light, medium, and heavy rain events were combined (Fig. 9). Overall, the greatest retention percentage (87%) occurred at 2%–4 cm.

When light, medium, and heavy rain events were cate-

Table 3. Percentage of total rainfall retention over the 14-mo period (28 Aug. 2002 to 31 Oct. 2003) from four roof platform treatments replicated three times.

Treatment†	Light‡	Medium	Heavy	Overall
	%			
2%–2.5 cm	95.1	82.9	64.7	69.8
2%–4.0 cm	97.1	85.5	65.1	70.7
6.5%–4.0 cm	94.9	83.1	59.5	65.9
6.5%–6.0 cm	95.8	84.6	62.0	68.1

† Values denote retention from vegetated roof platforms set at a 2% roof slope with 2.5 cm of media (2%–2.5 cm), 2% roof slope with 4 cm of media (2%–4 cm), 6.5% roof slope with 4 cm of media (6.5%–4 cm), or 6.5% roof slope with 6 cm of media (6.5%–6 cm).

‡ Rain event categories are light (<2 mm) ($n = 26$), medium (2–6 mm) ($n = 30$), heavy (>6 mm) ($n = 27$), and overall ($n = 83$).

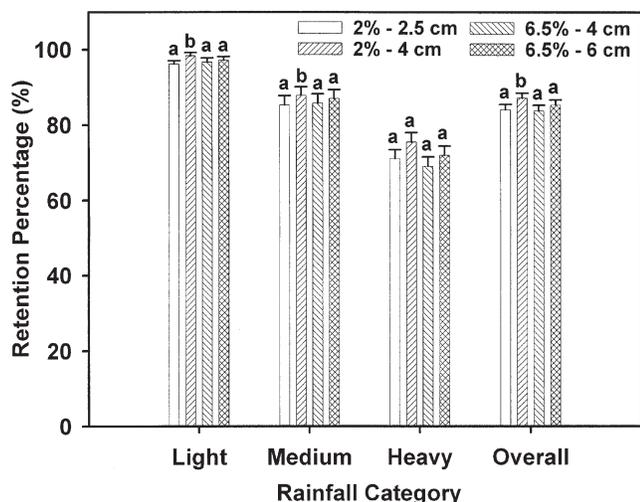


Fig. 9. Retention percentage (%) for all measured rain events in respective categories (light, $n = 26$; medium, $n = 30$; heavy, $n = 27$; overall, $n = 83$) for each roof slope and media depth treatment. Treatments were as follows: 2% roof slope with 2.5 cm of media (2%–2.5 cm), 2% roof slope with 4 cm of media (2%–4 cm), 6.5% roof slope with 4 cm of media (6.5%–4 cm), and 6.5% roof slope with 6 cm of media (6.5%–6 cm). Letters above bars represent mean separation among treatments within each rainfall category by Tukey's Studentized Range (HSD) test, $P \leq 0.05$, $n = 3$. Error bars represent standard error symmetrical around the mean, but only the positive side is shown on the graph.

gorized, the lowest retention percentage occurred during heavy rain events (69.2–75.6%). Light rain events resulted in the highest retention percentage where more than 96% of the rainfall was retained regardless of roof slope or media depth. The lowest retention percentage recorded during the study was 22%, which occurred during a 2.37-mm rain event. One hundred percent retention occurred on several occasions with rainfalls up to 5.8 mm. The heaviest rain event, 73 mm, occurred on 3–5 Apr. 2003. Thirty percent of the rain from this event was retained when averaged over all four treatments.

Retention percentages for light and medium rain events were greatest on the 2%–4 cm platforms ($P \leq 0.05$). The other three treatments were not different from each other in these rainfall categories. For heavy rain events, no difference was detected between treatments. The 2%–4 cm treatment had the highest mean retention percentage when all rain events were combined across rainfall categories. The other treatments were again not significantly different from each other.

DISCUSSION

Study 1

It was hypothesized that the gravel ballast roof would yield considerably more runoff than the other two roof treatments, but it was unclear if vegetation would be significantly different compared with the media-only treatment. As expected, the gravel ballast roof retained less water in all rainfall categories when compared with the other two roof treatments on both a per rain event basis and for total rainfall. This occurrence is probably due to the high surface area of the expanded slate-based media,

which is very porous and allows for a higher water holding capacity relative to the open spaces within the gravel ballast typically found on conventional roofs (Liesecke, 1998). The largest difference between the vegetated and gravel ballast treatments occurred during medium rain events when the vegetated treatment retained an average of 48% more water per rain event. The media-only and vegetated treatments were not significantly different when the rain events were categorized. This suggests that the main factor for water retention is the physical properties of the media as well as the presence of the water retention fabric. In this experiment, approximately 40% of the substrate was composed of retention fabric.

The vegetated treatments retained 60% of the rainfall they received during the measured rain events, which is about 10% higher than the findings of Monterusso et al. (2004), but similar to the findings of Liesecke (1998) and Schade (2000) when similarly designed green roof systems were used. The discrepancy between this study and that of Monterusso et al. (2004) is probably due to the lower number of rain events measured in the Monterusso et al. (2004) study. Past studies have offered results of retention per year percentages. However, they are not possible with the data collected from this study because the tipping bucket rain gauges did not function properly in temperatures below 0°C. However, we could assume lower retention percentages during the winter months in a locale such as Michigan, because evapotranspiration and soil infiltration are greatly reduced during this time (Liesecke, 1998).

Several studies have shown a delay in peak flow of runoff from a green roof when compared with a standard roof (Liesecke, 1999; Moran et al., 2003; Schade, 2000). From both plots during the representative heavy rainfall event (Fig. 4 and 5), we can see that a delay in the onset of runoff on the green roof treatment is evident when compared with the gravel ballast. No delay can be seen for the light and medium rainfall events due to the green roof treatments retaining nearly all of the rainfall. The cumulative hydrographs offer another valuable method of looking at the reduction green roofs provide. In all three cumulative hydrographs, runoff from the gravel ballast treatment is evident unlike the representative plots for the media-only and vegetated treatments. The peak flow reduction and the tendency to extend the runoff over longer periods is very important for storm-water management because the total amount of water and rain event duration is often not the problem, it is the rate that the incoming water needs to be treated.

Results of this study support earlier findings that green roofs can reduce runoff from buildings. Past studies have indicated that media depth plays an important role in water retention (Liesecke, 1998). From this information, we can imply that media and/or water retention fabric is one of the most important factors for water retention. To our knowledge, the effect of vegetation relative to media-only has not been studied even though it has generally been believed that vegetation plays a large role in water retention. However, our findings indicate that vegetation is much less of an effect in aiding water retention when compared with media. Even so, vegetation plays

other important roles such as preventing erosion of the media from wind and water and providing transpirational cooling and shade for the building, as well as mitigating the urban heat island (Lükenga and Wessels, 2001; Dimoudi and Nikolopoulou, 2003).

Study 2

Although Schade (2000) found similar runoff coefficients between four roof slopes using a vegetated mat green roof system, we hypothesized that increasing roof slope would increase the quantity of runoff and that this occurrence could be offset by increased media depth.

As expected, platforms built on a 2% slope containing 4 cm of media retained a greater quantity of rain than the others on both a per rain event basis and for total rainfall. Retention percentage for this treatment was significantly greater than the others in all rainfall categories except heavy events. Although the difference was significant, the difference from other treatments was minimal. No treatment consistently yielded the lowest retention value in all rainfall categories.

Overall, at the 4-cm depth the treatments on a 2% slope retained significantly more water than the 6.5% slope treatments. This finding contradicts those of earlier studies. Schade (2000) reported nearly constant water retention rates for roof slopes ranging from 2% up to 58%. Liesecke (1999) generalized that annual retention rates of 55 to 65% on an 8.7% sloped roof are comparable to a 2% slope. The difference in findings between past and current studies could be due to differences in media composition among the studies.

Increasing media depth increased water retention at only one slope. Retention percentages for platforms with 6 cm of media were not different from platforms with 4 cm of media on the 6.5% roof slope. However, for the 2% roof slope, deeper media (4 cm) retained a significantly greater percentage of water for both the light and medium rainfall categories, but not heavy ($P \leq 0.05$). Together with past studies, we can establish that increasing media depth usually increases retention (Liesecke, 1998).

Media depth should be considered for reasons other than just stormwater retention. In Quebec, Boivin et al. (2001) found that substrate depth can influence freezing injury in certain herbaceous perennials. The researchers concluded that in their climatic region, a minimum substrate depth of 10 cm should be used for the green roof system constructed for their study. Other studies found that media depth influences the growth, drought stress, and drought tolerance of green roof vegetation (Durhman et al., 2004; Lassalle, 1998; Monterusso et al., 2005; VanWoert et al., 2005).

As mentioned previously, several studies have shown a delay in peak flow of runoff from a green roof when compared with a standard roof (Liesecke, 1999; Moran et al., 2003; Schade, 2000). However, Fig. 8 shows that the effect of roof slope and media depth on runoff delay is minimal for rain events greater than 2 mm. This implies that once sufficient rainfall has occurred to reach the media's water holding capacity, additional rainfall

will leave the roof as runoff regardless of media depth. The only observed runoff delay among treatments occurred during the representative light rain event. From the results of this and previous studies, we can speculate that roofs with deeper media provide a greater delay in runoff due to increased water holding capacity.

Past studies have indicated that media moisture content immediately before a rain event influences the amount of water retained (Monterusso et al., 2004; Moran et al., 2003). Rainfall intensity and duration also play a part in water retention. Media moisture content, rainfall intensity, and rain event duration likely explain differences between this study and others.

CONCLUSIONS

Vegetated platforms retained greater quantities of stormwater than the conventional roofs with a gravel ballast. While vegetation did affect stormwater retention, it was minimal relative to the effects of growing media. Media depth also influenced water retention on our model-scale extensive green roofs at one of the tested slopes. Other studies that have considered the effects of media depth on water retention have found similar results. However, our finding that retention percentages were affected by the two slopes with equal media depths contradicts results regarding roof slope reported by Liesecke (1999) and Schade (2000). If the objective of a green roof is to maximize rainfall retention, then factors such as slope and media depth must be addressed.

Although green roofs are not new to other parts of the world, they are a promising new technology to mitigate stormwater runoff quantity and quality in the United States. They are a technology that should be considered for all roofing projects, especially those projects in areas where stormwater management is a concern for city planners. With the continual increase of area covered by impervious surfaces, the already important problem of stormwater management will only become more of an issue. Green roofs offer a new tool that shows promise as a technology that can aid in providing a sustainably built environment.

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REFERENCES

- Boivin, M., M. Lamy, A. Gosselin, and B. Dansereau. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. *HortTechnology* 11:409–412.
- Brenneisen, S. 2003. The benefits of biodiversity from green roofs—Key design consequences. p. 323–329. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29–30 May 2003. The Cardinal Group, Toronto.
- Bucheli, T.D., S.R. Müller, S. Heberle, and R.P. Schwarzenbach. 1998. Occurrence and behavior of pesticides in rainwater, roof runoff,

- and artificial stormwater infiltration. *Environ. Sci. Technol.* 32: 3457-3464.
- Dimoudi, A., and M. Nikolopoulou. 2003. Vegetation in the urban environment: Microclimatic analysis and benefits. *Energy Build.* 35:69-76.
- Dramstad, W.E., J.D. Olson, and R.T.T. Forman. 1996. Landscape ecology. Principles in landscape architecture and land-use planning. Harvard Univ. Graduate School of Design, Island Press, and Am. Soc. of Landscape Architects, Washington, DC.
- Durham, A., N.D. VanWoert, D.B. Rowe, C.L. Rugh, and D. Ebert-May. 2004. Evaluation of Crassulacean species on extensive green roofs. p. 504-517. *In Proc. of the 2nd North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Portland, OR. 2-4 June 2004. The Cardinal Group, Toronto.
- Gedge, D. 2003. From rubble to redstarts. p. 233-241. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.
- Giesel, D. 2001. Grün auf das dach-kosten in den keller? *Stadt Grün* 50:404-406.
- Graham, P., and M. Kim. 2003. Evaluating the stormwater management benefits of green roofs through water balance modeling. p. 390-398. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.
- Herman, R. 2003. Green roofs in Germany: Yesterday, today and tomorrow. p. 41-45. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.
- Johnston, J., and J. Newton. 1996. Building green. A guide for using plants on roofs, walls and pavements. The London Ecol. Unit, London.
- Lassalle, F. 1998. Wirkung von trockenstreß auf xerophile pflanzen. *Stadt Grün* 47:437-443.
- Liesecke, H.J. 1998. Das retentionsvermögen von dachbegrünungen. *Stadt Grün* 47:46-53.
- Liesecke, H.J. 1999. Extensive begrünung bei 5° dachneigung. *Stadt Grün* 48:337-346.
- Liesecke, H.J., and H. Borgwardt. 1997. Abbau von luftschadstoffen durch extensive dachbegrünungen. *Stadt Grün* 33:245-251.
- Liptan, T. 2003. Planning, zoning and financial incentives for eco-roofs in Portland, Oregon. p. 113-120. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.
- Lükenga, W., and K. Wessels. 2001. Oberflächentemperaturen von dachflächen. *Stadt Grün* 50:339-403.
- Mason, Y., A.A. Ammann, A. Ulrich, and L. Sigg. 1999. Behavior of heavy metals, nutrients, and major components during roof runoff infiltration. *Environ. Sci. Technol.* 33:1588-1597.
- Monterusso, M.A., D.B. Rowe, and C.L. Rugh. 2005. Establishment and persistence of *Sedum* spp. and native taxa for green roof applications. *HortScience* 40:391-396.
- Monterusso, M.A., D.B. Rowe, C.L. Rugh, and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. *Acta Hort.* 639:369-376.
- Moran, A., B. Hunt, and G. Jennings. 2003. A North Carolina field study to evaluate greenroof runoff quality, runoff quantity, and plant growth. ASAE Paper 032303. Am. Soc. of Agric. Eng., St. Joseph, MI.
- Niachou, A., K. Papakonstantinou, M. Santamouris, A. Tsangrasoulis, and G. Mihalakakou. 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy Build.* 33:719-729.
- Rosenfeld, A., H. Akbariand, J. Romm, and M. Pomerantz. 1998. Cool communities: Strategies for heat island mitigation and smog reduction. *Energy Build.* 28:51-62.
- Rowe, D.B., C.L. Rugh, N. VanWoert, M.A. Monterusso, and D.K. Russell. 2003. Green roof slope, substrate depth, and vegetation influence runoff. p. 354-362. *In Proc. of 1st North American Green Roof Conf.: Greening Rooftops for Sustainable Communities*, Chicago. 29-30 May 2003. The Cardinal Group, Toronto.
- SAS Institute. 2001. SAS Version 8.02. SAS Inst., Cary, NC.
- Schade, C. 2000. Wasserrückhaltung und Abflußbeiwerte bei dünn-schichtigen extensivbegrünungen. *Stadt Grün* 49:95-100.
- USEPA. 2003. Protecting water quality from urban runoff. EPA 841-F-03-003. USEPA, Washington, DC.
- VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, and L. Xiao. 2005. Watering regime and green roof substrate design impact *Sedum* plant growth. *HortScience* 40 (in press).
- Wong, N.H., Y. Chen, C.L. Ong, and A. Sia. 2003. Investigation of thermal benefits of rooftop garden in the tropical environment. *Build. Environ.* 38:261-270.
- Zobrist, J., S.R. Müller, A. Ammann, T.D. Bucheli, V. Mottier, M. Ochs, R. Schoenenberger, J. Eugster, and M. Boller. 2000. Quality of roof runoff for groundwater infiltration. *Water Res.* 34:1455-1462.